

CHARACTERIZATION OF BOREHOLES – RESULTS FROM A U-PIPE BOREHOLE HEAT EXCHANGER INSTALLATION

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Abstract: Heat exchange with the bedrock for ground source heat pumps is commonly done with the help of U-pipe energy collectors in vertical boreholes. At the moment, there exist many uncertainties about how efficient the heat transfer between the rock and the collector is. For a complete performance analysis of these systems, a 260 m deep water filled borehole is characterized, by measuring the borehole deviation, the ground water flow and the undisturbed ground temperature. Significant attention is devoted to detailed temperature measurements along the borehole depth during operation providing a complete description of the temperature variations in time both for the secondary working fluid and for the ground water.

The results show a deviated borehole from the vertical direction without any relevant ground water flow. The undisturbed ground temperature gradient varies from negative to positive at approximately half of the borehole depth. The transient response of the borehole during the heat pump start up is illustrated and it is observed that there does not exist any thermal short circuiting between the down and up-going pipes when the system is in operation.

Key Words: *heat pumps, U-pipe borehole heat exchanger, temperature, borehole, fiber optic, thermocouples, undisturbed ground temperature, borehole deviation*

1 INTRODUCTION

Under the surface of the earth there exists an energy source that can be used to efficiently heat and cool family houses and larger buildings, the bedrock. Until now, it has mostly been used as a heat source during the cold seasons.

What makes the bedrock an attractive heat source (and heat sink) is that it has near constant temperature along the year regardless of the ambient temperature variations. This allows having a reliable and long lasting resource which permits delivering a constant amount of heat with stable temperatures over the years.

The most common method to exchange heat with the ground is by means of an energy collector that is installed into a previously drilled vertical borehole. These energy collectors are also known as Borehole Heat Exchangers (BHE) and the most popular type consists of a closed U-pipe, through which a secondary fluid (normally an antifreeze solution such as water + ethanol) travels down and then up while collecting the heat from the bedrock. The thermophysical properties of these fluids are well known (Melinder 2007). The collected energy is subsequently delivered to the heat pump which upgrades and transports it up to the final use conditions. This type of system, ground source heat pump (GSHP), is widely used for heating in many countries in northern Europe nowadays.

Between 2003 and 2006, the geological survey of Sweden registered a total of 105125 wells of which 80,5% is for ground source heat pump usage (SGU 2008). It is estimated that 6 TWh/year of heat are given to the country by these systems with a coefficient of performance (COP) of around 3, which implies that the end users only pay for 1/3 of this energy. However,

the installation cost is relatively high, especially for drilling the hole, and methods for improving the efficiency must be determined, regardless of how popular this technology is today.

When analyzing the heat transfer performance under the ground, one must carefully look at the temperature difference between the rock and the secondary fluid outlet of the borehole. An increase of one degree Celsius of the out coming flow from the borehole gives a COP increase of approximately 3%. If the temperature difference between the ground and the evaporating temperature is lowered by 3 °C the COP of the heat pump would improved by 8 to 10%, which implies an electric energy saving of 0,2 to 0,4 TWh per year for Sweden , based on the statistics given above.

Conscious of this potential for improvement, all the uncertainties about what really happens under the ground and about the efficiency of the U-pipe energy collectors must be studied and the uncertainties clarified. One of the ways to do this is to carry out careful temperature measurements at research installations where the rock and the boreholes are carefully characterized so that all the factors that have a direct influence on the system can be identified. This paper presents the characterization and initial results of a typical U-pipe heat exchanger installation in a 260 meter water filled borehole, where the groundwater conditions, the undisturbed rock temperature and the borehole deviation are measured. The system has just recently been installed and there are limited data available at this time. After startup of the system, detailed temperature profiles are measured in the borehole and in the secondary fluid.

2 ASPECTS TO CONSIDER WHEN CHARACTERIZING BOREHOLES

In order to characterize a borehole in detail it is appropriate to observe the borehole cross sections along its depth so that different factors influencing the heat transfer can be identified. These factors are the ground thermal properties (e.g. the rock thermal conductivity), the groundwater conditions around the BHE, the borehole characteristics (diameter, depth, and deviation), the BHE material and geometry, the temperature profile of the circulating fluid and its flow conditions (laminar or turbulent). The outcome of these aspects has a direct influence on the temperature of the secondary fluid that comes back to the heat pump after traveling along the BHE.

2.1 Temperature Profile

Diverse heat transfer conditions might occur at different cross sections along the borehole length and these affect the energy exchange at different segments. The driving force for the heat flow is the temperature difference between the wall of the borehole (rock surface) and the secondary fluid. The ratio between this temperature difference and the consequent heat flow is known as borehole thermal resistance. When a bedrock coupled heat pump system is in operation, the thermal resistance of the borehole can vary with depth and the temperature profiles on both sides of the BHE must be measured at as many points as possible. An undesirable phenomenon that can occur is the so called thermal short circuiting effect between the collector pipes that occurs when heat is transferred from the upcoming to the down coming pipe. This may cause temperature drop in the circulating fluid and will decrease the system efficiency. Therefore, the thermal resistance between the down and up going fluid flowing through the pipes must be as high as possible, in contrast to the correspondent value for the borehole where a lower thermal resistance represents a smaller necessary temperature difference between the bedrock and the heat carried fluid for a given power (Gehlin S 1997).

In order to make an overall cross section picture of the temperature profiles between the bedrock and the secondary fluid, it is first necessary to measure the corresponding values for the undisturbed ground, normally measured before the system is started. It can also be determined by circulating the secondary fluid through the BHE for a sufficiently long period so that its temperature reaches a balance with the ground.

Although temperature measurements are the best indicator when evaluating the heat transfer performance with the ground, they might need to be justified by measuring the bedrock's thermal properties and external factors such as geometrical characteristics and the ground water flow differences along the borehole.

2.2 Thermal Properties of the Ground

The bedrock thermal properties can be determined based on theoretical, laboratory or field measurements (in situ). In situ measurements of borehole thermal properties are a better approximation to the reality in view of the fact that many ideal assumptions are made when making mathematical models (Gehlin 1998). There are factors which alter the heat transfer conditions such as presence of rock fissures around the borehole, resulting in natural convection on the groundwater side, borehole deviation from the planned direction, varying thermal conductivity in the rock, direct contact between the BHE pipes in the borehole, among others. These issues indicate that it is difficult to trust laboratory measurements on rock samples and mathematical models to the highest extent since the exact underground conditions are commonly unknown.

(Mogensen 1983) presented an in situ method that consists of circulating a fluid through the BHE while simultaneously extracting a constant heat power so that the fluid is cooled in a controlled way. This method is widely used today, better known today as Thermal Response Test (TRT), but most popularly carried out by supplying heat to the fluid instead of extracting it. By measuring and registering the values of supplied heat, outdoor temperature, secondary fluid flow, and the borehole incoming and outgoing temperatures, it is possible to finally determine the thermal conductivity of the ground and the borehole thermal resistance by using a line source model (Gehlin S 1997).

2.3 Groundwater Flow

The presence of groundwater in the borehole greatly influences the thermal resistance between the rock and the circulating fluid since it determines the section of the borehole heat exchanger that will be exposed to effective heat transfer. The active borehole length, is the part of the borehole that is filled with groundwater. The heat transfer from the rock to the secondary fluid is radically better in this region since the thermal conductivity of water is approximately 20 times higher than that of air at the temperature conditions in the borehole. Moreover, groundwater movement around the BHE increases the convection heat transfer coefficient in the water side of the borehole. This movement can occur by natural convection occurring due to ground water density differences along the borehole length and also due to the presence of cracks around the borehole that might cause an improvement of the heat transfer at local sections. Such water flow in cracks may also substantially influence the apparent thermal conductivity of the rock.

2.4 Borehole Deviation

As boreholes are usually not absolutely straight they do not normally reach the desired depth. Presence of rock cracks can suddenly change the drilling orientation and guide it towards its own planes. Deviation in direction can also be associated with the drilling method and equipment, i.e. the type of drill and drill accessories, rotation velocity, uncontrolled or excessive push down, the driller experience, and the initial position of the drilling hammer. It

is important to be conscious about this reality since a large borehole deviation might cause slight ground water temperature change with respect to the value at the desired depth. Moreover, it might originate legal problems as well as unexpected thermal influence by other boreholes located under neighbor land surfaces since the thermal influence between two boreholes is proportional to the distance between them. Lastly, the deviation might cause that the BHE pipes rest on one of the borehole sides having better contact with the borehole wall to a certain extent.

3 DESCRIPTION OF THE EXPERIMENTAL BOREHOLE

The evaluated borehole is located in the south of Stockholm, Sweden, at an installation with a total of 6 boreholes separated from each other at the surface level by at least 4 meters. According to (SGU 2008), the type of rock surrounding the borehole is gneiss or possibly granite. The thermal conductivity values for this rock type vary between 2,5 and 4,7 W/mK. A thermal response test is expected to determine its exact value.

The borehole diameter is 140 mm and its total length is 260 m. Its ground water level oscillates around 5,5 m, giving an active borehole length of approximately 254, 5 m.

The borehole is equipped with a polyethylene U-pipe BHE of the type PE 40x2,4 mm, with thermal conductivity of 0,42 W/mK. It has been filled with a water solution of 20% ethanol volume concentration. This concentration provides a freezing point of -8°C (Melinder 2007). The working temperature of the fluid during operation will determine its exact thermophysical properties along the BHE.

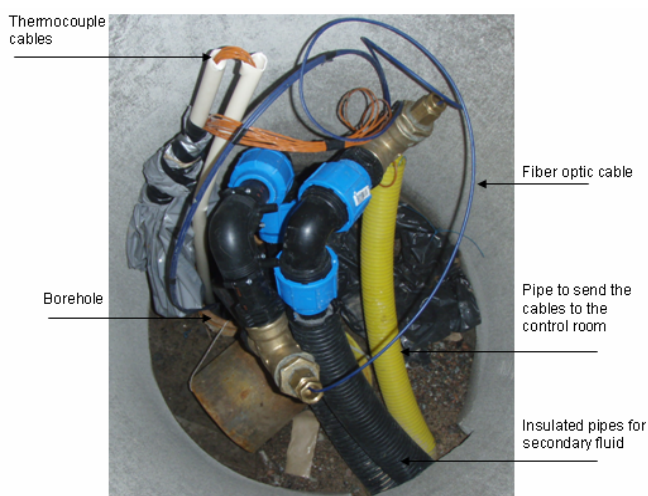


Figure 1: Overview of the borehole components

For the temperature measurements, the borehole is instrumented on the groundwater and the secondary fluid side with optic fiber cables (50/125 - graded index - Multimode Optical Fiber for Distributed Temperature Sensing (DTS). Temperature measurement by optical fibers is a technology that has been used in oil wells and in dams, but which has scarcely been used for geothermal boreholes and aquifer monitoring (John S. Selker 2006). In the optical fiber cables, a signal is sent in the form of laser light rays that propagates along the fiber and experiences a loss during propagation due to absorption, scattering and reflection. The light is guided to the measurement zones where it is modulated by the temperature according to Raman scattering principle and returned along the same optical fiber to the reading equipment which is of the type Sentinel-DTS from Hydroresearch AB. This system can examine the temperature distribution along the entire cable length, with a precision (spatial resolution) of 1 m and with an accuracy of around 0.05°C. The resolution of the measurements is of around 0.02°C.

On the secondary fluid side, T type stainless steel sheathed thermocouples are also inserted into the pipes at 15, 55, 130, 220 m in each tube and at the collector bottom. The thermocouple cables are taken through plastic pipes to the top of the borehole and connected from there, through a temperature box (which contains a circuit with an internal reference given by a PT-100 meter) to an Agilent data acquisition unit that reads the measurements. Figure 1 shows an overview of the borehole seen from the top where the sensor cables can be observed as well as the connection between the U-pipe collector with

the insulated pipes through which the secondary fluid travels towards and from the heat pump.

4 THE CHARACTERIZATION RESULTS

4.1 Borehole Deviation

The borehole deviation measurements were done with an instrument of the type FLEXIT MultiSmart which orientates itself after the earth magnetic field when it is sent down into the borehole. The instrument registers mainly the dip angle, which is the inclination between 0 and $\pm 90^\circ$, and the azimuth angle which is the direction between 0 and 360° relative to the earth magnetic north. With these, the Cartesian position parameters x, y and z, are calculated at each measurement point.

Measurement points were taken every 10 meters over the whole borehole length. This gave a total of 26 measurement points.

The borehole deviation at the last measurement point (260 meters away from the top) is 56,4 m and 30,5 m towards east and north respectively, as shown in Figure 2 where the 26 points are plotted for the x (northward) and y (eastward) directions.

Figure 3 illustrates the deviation of the borehole under study (denoted with the name BH4) together with other neighbour boreholes. The black lines represent the expected vertical direction which is 260 meters deep. It can be observed that BH4 did not reach the desired depth. Instead, the end of the borehole is 9,65 m above the expected level, i.e. the depth is 250,35 m. The borehole deviation increased while drilling which might normally be the usual case. Since the real achieved depth is not guaranteed, it is of convenience to refer to borehole length instead of borehole depth when referring to the total distance from the borehole top to the bottom.

During this test, the temperature of the ground was also registered at the 26 measurement points and the results are presented in the subsection “undisturbed ground temperature”, together with temperature measurements from the optic fiber cable.

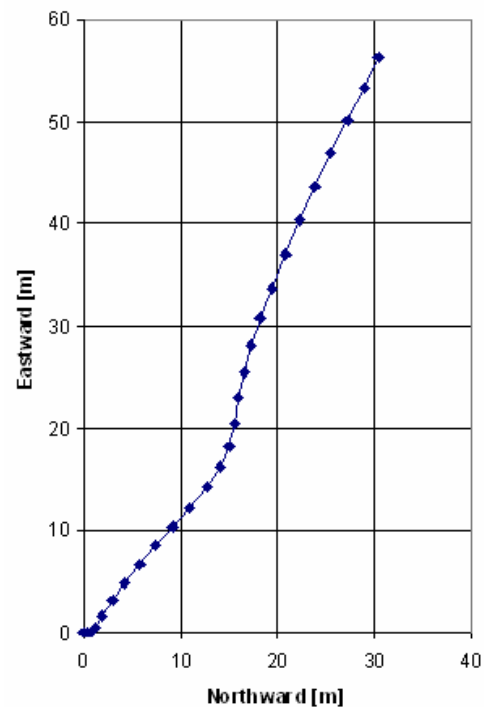


Figure 2: Deviation of the borehole towards north and east direction

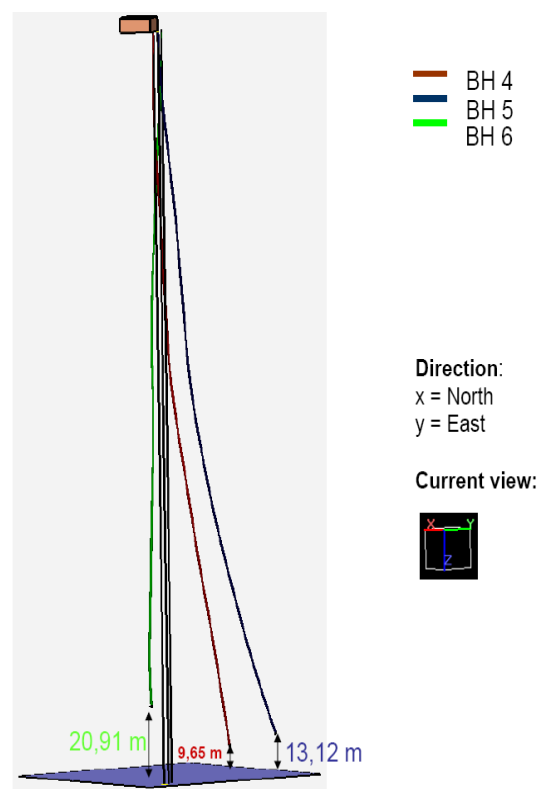


Figure 3: Deviation of the borehole with regard to the vertical direction

4.2 Groundwater Flow Measurement

Maps from the Geological Survey of Sweden (SGU 2008) state that, in the area where the borehole installation is located, the average constant possible groundwater extraction is under 10 liters/minute. This can vary from well to well depending on the presence of local water flow through rock cracks. However, this value is an indication of what groundwater flow magnitudes could be expected in this region.

The groundwater flow at this specific borehole is measured by pumping out water at a sufficiently low flow so that the ground water level stays constant due to its balance with the borehole incoming groundwater. The flow at different depths was measured with a flow logging equipment from GEOSIGMA AB that basically consists of a cylindrical probe (see Figure 4 and Figure 5) with an inbuilt propeller located in its inner part. The measurement is carried out by first decreasing the water level in the borehole to create an inward water flow and then sending down the probe at a known velocity and registering the rotation rate of the propeller which might vary due to the presence of local groundwater flow at certain sections of the borehole. The propeller rotation is registered and subsequently related to the groundwater flow conditions.

It can be seen in Figure 5 that the instrument has a rubber disk on its external wall in order to ensure that the ground water flows through the probe propeller and not between the probe and the borehole wall, so that the flow measurement becomes as exact as possible. Moreover, the white bands located parallel to the metal cylinder are used to center and steer the instrument into the borehole, as observed in Figure 4.

The results from this measurement are shown in Figure 6. The flow logging activity could not be carried out either when keeping the groundwater level at its original conditions nor when it was lowered to 22 m. The water level was then reduced to 35 m with respect to its original level and, at this point, although the current flow was very low (0,5 l/min), a logging process was carried out. It is observed that a lower flow value was registered between 190 and 200 m. The borehole is considered to be tight and without presence of significant groundwater flow, as it was only about 0.4 l/min after decreasing the ground water level by 35 meters.



Figure 4:
Flow logging
probe
insertion
into the
borehole



Figure 5: Flow
logging probe

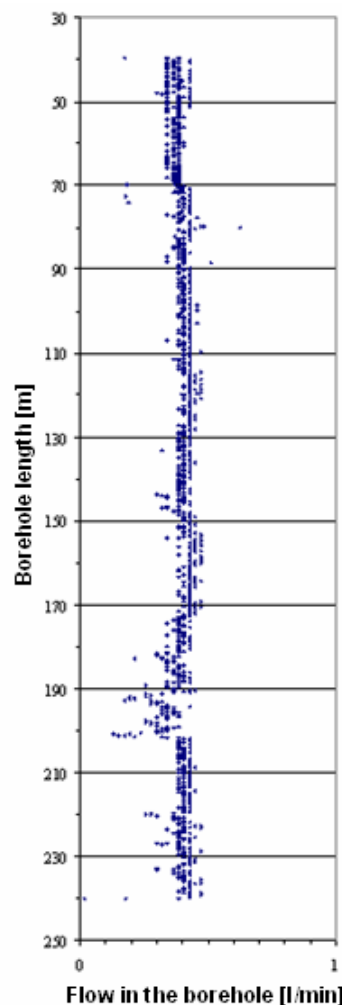


Figure 6. Ground water flow along
the borehole length

The minimum flow value which allows finding anomalies (fractures, fissures, cracks) around the borehole for the used equipment is 2 l/min and therefore, no anomalies were localized during the test. However, the results from Figure 6 show that there is a possible small increase in the borehole diameter at a depth between 190 and 200 m since a lower flow was registered.

4.3 Undisturbed Ground Temperature

The groundwater temperature was measured every 5 minutes during eight hours before the borehole was put into operation. This measurement was done with an optic fiber cable that was installed in parallel with the borehole heat exchanger. The total measured borehole length is 247,8 meters and the results of the measurements are shown in Figure 7, where it can be observed that the temperature approximately increases 2,5 degrees in the first 10 meters. Moreover, the temperature gradient between 10 and 110 meters is negative, i.e. the temperature decreases in the region from 10,5 to 8,7 °C. At this depth (110 m), the undisturbed ground temperature has a minimum and then, the gradient becomes positive until almost 250 meters depth. The date when this measurement was done is December 17th, 2007. Besides this, the undisturbed ground temperature was measured the 22nd of May 2007 with the FLEXIT instrument every 10 meters while measuring the borehole deviation. These points are also shown in Figure 7, where the same general profile can be observed. However, the temperature was not as low at the surface level since the measurement was taken during a warmer season and the ambient temperature is normally higher during May than December. The minimum temperature with this instrument is registered at a depth between 140 and 150 m.

The ground water level is around 5,5 m under the surface which makes the first 6 – 8 meters of borehole sensitive to ambient conditions.

The temperature resolution of the results from the FLEXIT instrument is 0,5 °C while for the fiber optics it is 0,02 °C, which might explain the difference between the two measurement methods. The temperature values are not shown after a 250 m depth for the latter instrument because the fiber does not reach the total borehole length. Instead, 247,8 m are covered.

It is important to mention that in the theory about bedrock undisturbed ground conditions, it is stated that the temperature gradient is positive after the

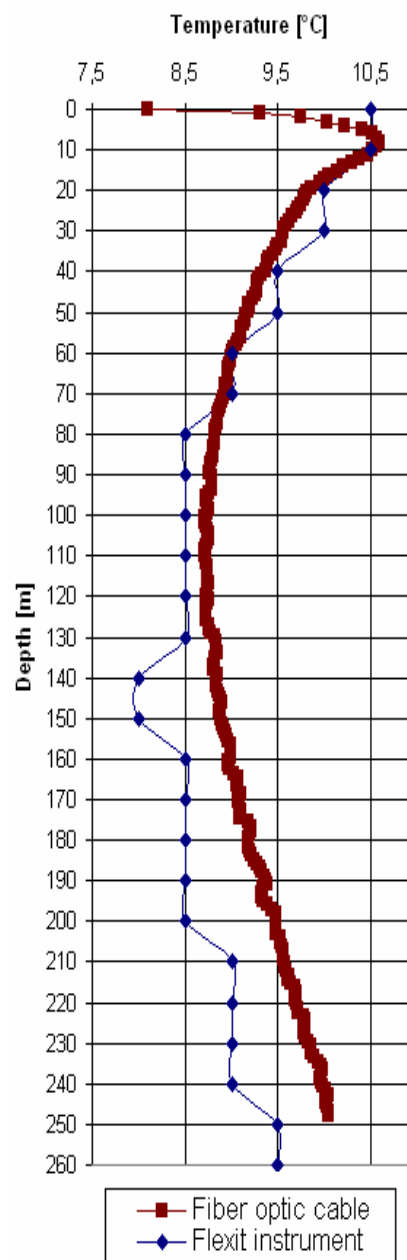


Figure 7. Undisturbed ground temperature

first 15 meter of depth. However, this was the case only for the segment between 110 and 250 meters of borehole depth where the gradient is approximately 1°C /100 m.

4.4 Borehole Temperatures Under Operation

As already mentioned, the borehole is instrumented on the ground water and the secondary fluid side with optical fibers and also with T type stainless steel thermocouples located in the center of the pipes at different depths for temperature measurements.

The exact length of the U-pipe collector is 257 meters since some extra weight was added to the collector bottom during its installation. The internal fiber optic cable measures along the whole collector length and the external cable measures the ground water temperature until a depth of 247,8 meters. The DTS is configured to measure every one meter and therefore, approximately 257 measurement points are taken in each collector pipe. Since the external fiber cable is doubled, the total amount of measurement points in the ground water side is 496. Moreover, temperature values are taken with thermocouples located at 15 m (T402 and T410), 55 m (T403 and T409), 130 m (T404), 220 m (T405 and T407) and at the collector bottom (T406). The nomenclature of these points is according to the flow direction, i.e. T402 and T410 are the first and last measurement points, respectively. Figure 8 shows the average temperatures inside the borehole on both the secondary fluid and ground water side measured every 10 minutes during 26 days.

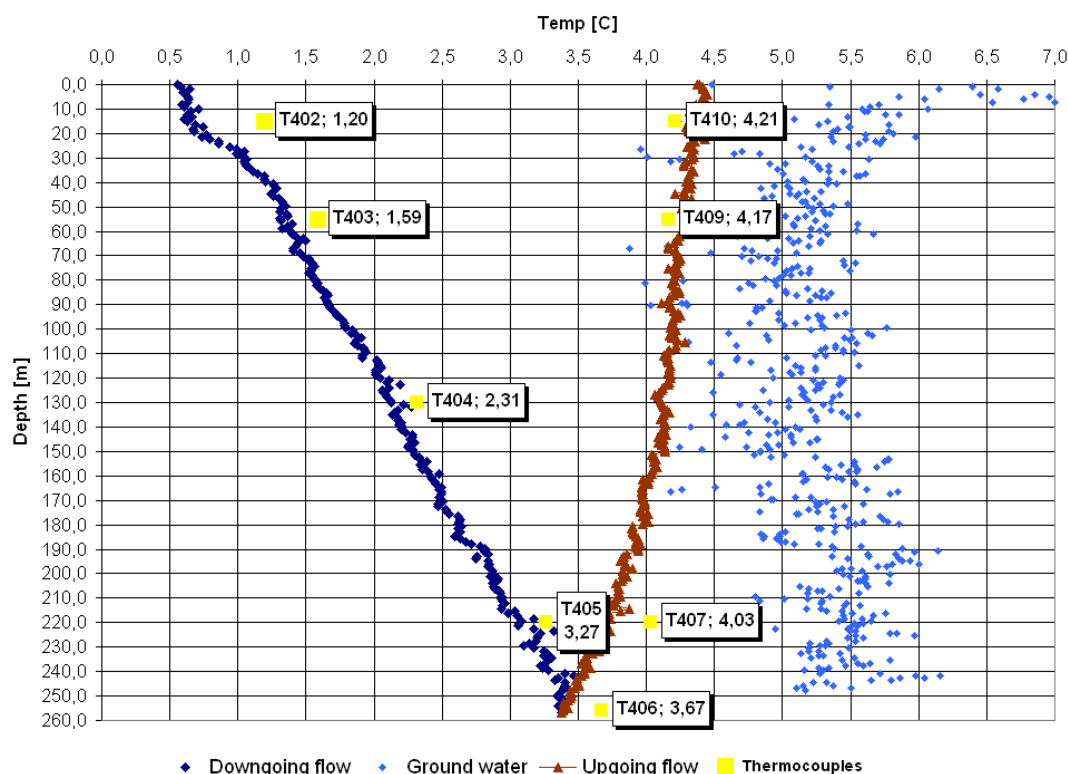


Figure 8: Average temperatures along the borehole during the first month of operation

It can be observed in Figure 8 that the fluid temperature constantly increases during its trajectory through the BHE. The inlet and outlet temperatures are about 0,6 °C and 4,4 °C, respectively, while the corresponding value at the collector bottom is 3,4 °C. Nevertheless, the temperature change in the way down is significantly higher compared to the up going flow. At the same time, the ground water temperature mostly oscillates between 4,5 °C and 6,0 °C. The latter is accredited to the fact that the optic fiber cable exact location in the borehole is unknown, i.e. the cable might be located close to the borehole wall at some points whilst next to the BHE wall at some others.

The difference between the readings from the thermocouples and the fiber optics is 0,7 °C in the worst case. This can be in part attributed to the location of the measurement point since

the thermocouple point is located exactly in the middle of the tube and the optic fiber cable might be measuring close to the pipe wall. This makes a difference if the secondary fluid flow regime is laminar. Nevertheless, it is not a significant problem if the fluid flow is turbulent because the temperature profile in this case is even across the pipe section.

When making continuous measurement with optic fibers, it is possible to have a detailed picture of the temperature changes at any borehole location during any specific time. Figure 9 illustrates the secondary fluid temperature change in the down going pipe during a typical operation cycle of the borehole. These measurements were taken every two minutes for a period of 2 hours during the 3rd operation day of the system.

In Figure 9, during the period between 0 and 20 minutes, the heat pump is in operation and the fluid temperature goes from 0 to approximately 4 degrees between the top and the bottom of the collector. This profile changes slowly between minute 20 and 80 when the heat pump is not in operation and it can be observed that the temperature values along the borehole length start to balance themselves becoming warmer (approaching the ground water temperature) until almost the whole borehole has an average temperature of about 5 °C.

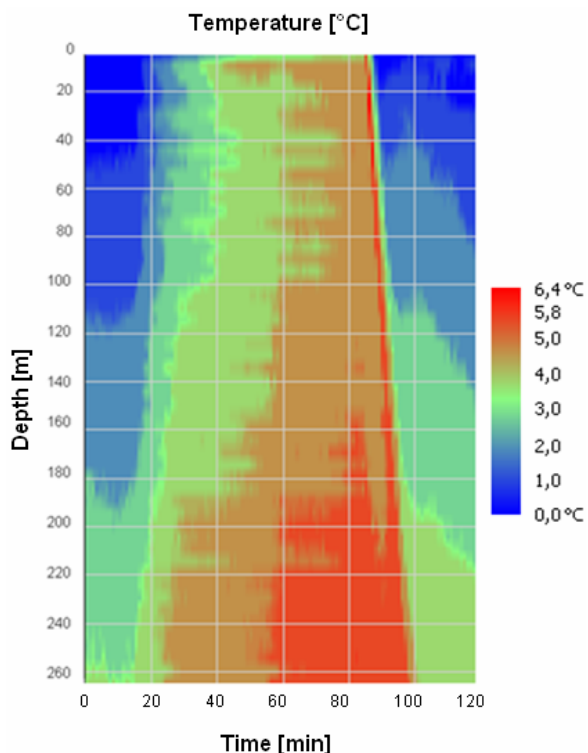


Figure 9: Secondary fluid temperature profile during borehole operation cycle

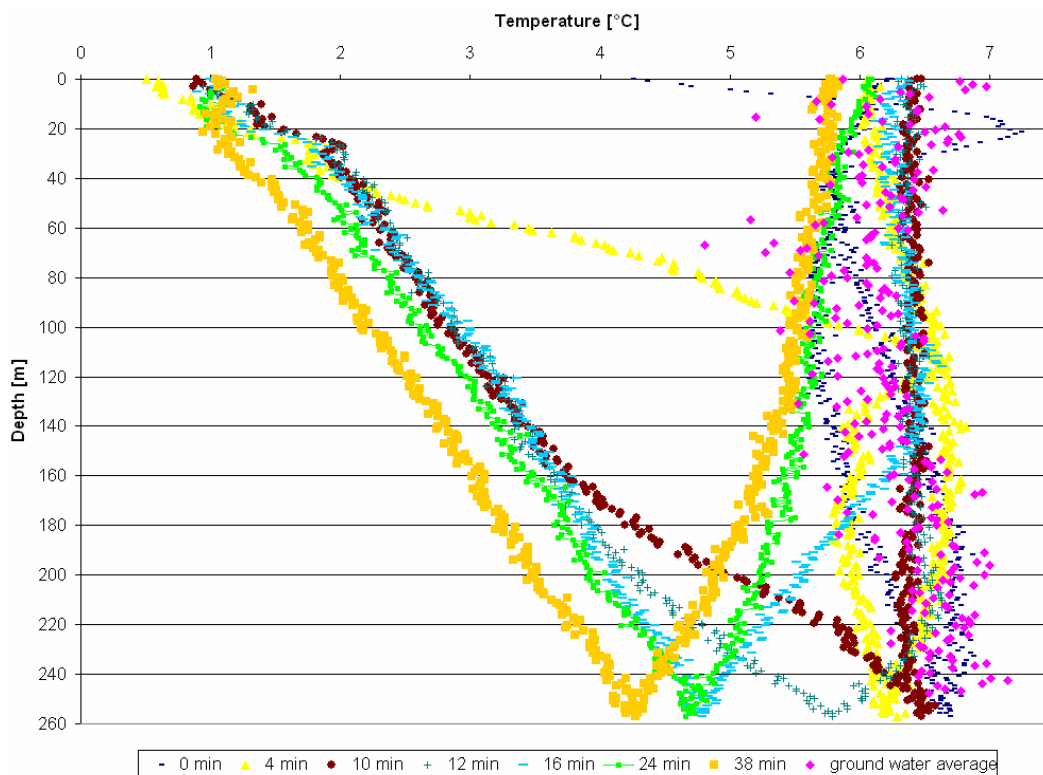


Figure 10. Temperature of secondary fluid and ground water during the system start up

The heat pump starts once again during the last 30 minutes and the temperature changes first take place at the upper part of the BHE and propagate with time to the collector bottom. The latter is also illustrated for the same period in Figure 10, where it is observed that the secondary fluid temperature during minute zero is approximately the same as for the groundwater over the whole borehole length (about 6 °C) and that the temperature difference between the borehole inlet and outlet changes as soon as the heat pump starts to extract the energy from the secondary fluid. Most of the energy (approximately 65%) is collected in the down going pipe while the rest is collected when the fluid is coming back up towards the borehole top. It is important to mention that, at these working conditions, the fluid temperature always increases along the borehole length after the first 4 minutes of operation, which indicates that it warms up and that no thermal short circuiting occurs.

5 FUTURE WORK

This paper reflects part of the first stage of a project called “Efficient Use of Geothermal Wells for Heat Pumps” which has as general goal to point out recommendations for design and installations of collectors in boreholes for heat pumps. The project target is to decrease the temperature difference between the ground and the evaporation temperature of the refrigerant in the heat pump by 3 °C, so that Ground Source Heat Pumps improve their COP between 8 to 10%.

The characterization and instrumentation of this borehole is a perfect starting point for a complete understanding of what happens under the ground with today's U-pipe borehole heat exchangers. All these parameters are going to be correlated to each other in order to understand their influence on the secondary fluid profile.

This borehole will be tested under different secondary flow regimes forced by an extra circulation pump and controlled with valves and advanced flow measurement equipment to finally find correlations between the ground thermal properties, the ground water conditions around the BHE, the borehole characteristics, the BHE material and geometry, the temperature profile of the circulating fluid and its flow conditions (laminar or turbulent). The outcome of these aspects has a direct influence on the temperature of the secondary fluid that comes back to the heat pump after traveling along the BHE. The thermophysical properties of the secondary fluid will be specified for each of the BHE sections according to their working temperature so that accurate heat transfer analysis can be carried out. These results will be used as a reference for performance comparison among different type of borehole heat exchangers.

6 CONCLUSIONS

In order to understand what happens under the ground in borehole installations for heat pumps, it is necessary to characterize the boreholes regarding the rock thermal properties, the groundwater conditions around the BHE, the borehole characteristics, the BHE geometry, the temperature profile, flow conditions and thermophysical properties of the circulating fluid.

Temperature measurements with optic fiber cables were made in both the secondary fluid and groundwater side of a borehole, and provided a detailed picture of the temperature profiles and their behavior in time. No short circuiting effect is observed between the BHE pipes during the first month of operation.

The undisturbed ground temperature has a negative gradient during the first 110 m of depth and then the temperature increases until with a rate of 1°C/100 m. The correspondence

between the temperature measurements with optic fiber cables and thermocouples varies between 0°C and 0,7 °C and this is attributed to differences in the measurement principle and to possible contrast between the flow regime and the location of the measurement point.

The borehole under study is deviated 56, 4 m and 30, 5 m towards east and north from the vertical direction, respectively. Similar values were measured for the other boreholes of the installation.

No significant ground water flow takes place in the studied borehole. It was registered to be approximately 0,4 l/min along the borehole length and no local effects due to groundwater flow differences along the borehole length are detected.

The continuation of this work consists of correlating temperature with flow measurements and finding their analogy to the borehole characteristics. Different collector types will be as well characterized, analyzed and compared in order to point out recommendations for design and installation in boreholes for heat pumps.

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